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STUDIES FOR STUDENTS.

THE PRINCIPLES OF ROCK WEATHERING.

1. Preliminary generalities.
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(1) PRELIMINARY GENERALITIES.

IN the series of papers to be given under the above title it is proposed to discuss briefly the principles involved in the breaking down of rock-masses when subjected to the ever varying conditions commonly grouped under the name of "weathering."

So striking a phenomenon as the disintegration of a mass of firm rock, naturally did not escape the observation of the earlier workers in geology, and the older literature, from the time of Hutton, bears numerous references to it, though the full significance of atmospheric agencies in bringing about the result, seems not at first to have been fully realized. Indeed the earliest satisfactory accounts to which we have access, are those of writers of the present century, which are based largely upon observations made in moist and warm climates, where the results of such weathering are most apparent.

The exciting cause of this degeneration has been a matter of considerable speculation, and, before proceeding further, it may be well to indicate in brief their tendencies.

Fournet, as quoted elsewhere, writing as early as 1833, insisted upon the efficacy of water containing carbonic acid in

promoting the decomposition of igneous rocks, while Brongniart, writing with particular reference to feldspathic decomposition and the origin of kaolin, laid great stress on the acceleration of the ordinary processes of decay through the electric currents resulting from the contact of heterogeneous rock-masses. Darwin¹ believed the extensive decomposition observed by him in Brazil, to have taken place under the sea, and before the present valleys were excavated. Hartt² gave it as his opinion that the decomposition was due to the action of warm rain water soaking through the rock and carrying with it carbonic acid derived not only from the air, but from the vegetation decaying in the soil as well, together with organic acids, nitrate of ammonium, etc. Further that the decomposition had gone on only in regions once covered by forests. Heusser and Claraz,³ suggest that the decomposition was brought about through the influence of nitric acid. They say "it is without doubt determined by the violence and frequency of the tropical rains, and by the dissolving action of water, which increases with the temperature. It is necessary to observe, moreover, that this water contains some nitric acid, on account of the thunder storms which follow each other with great regularity during many months of the year."

Belt⁴ in discussing the extensive decomposition observed by him in Nicaragua says "This decomposition of the rocks near the surface prevails in many parts of tropical America, and is principally, if not always, confined to the forest regions. It has been ascribed, and probably with reason, to the percolation through the rocks, of rain water charged with a little acid, from the decomposing vegetation."

The elder Agassiz⁵ laid much stress on the decomposing effects of hot water from rainfall, while Mills⁶ attributed no

¹ Geological Observations, p. 417.

² Physical Geography and Geology of Brazil.

³ Ann. des Mines, 5^e Series, 17^e, 1860.

⁴ The Naturalist in Nicaragua. 1874.

⁵ Jour. in Brazil, p. 89.

⁶ Am. Geologist, June 1889, p. 351.

insignificant amount of the decomposition to the action of carbonic acid produced through the instrumentality of ants.

The chemical changes involved in the process of decomposition received attention from several of the earlier workers, among whom the names of Berthier, J. G. Forschhammer, Brongniart, Gustav Bischof and Ebelmen stand out in greater prominence. More recently the name of Sterry Hunt becomes conspicuous, while the purely geological side of the question has been set forth in numerous papers by De La Beche, L. Agassiz, R. Pumpelly, N. S. Shaler, O. A. Derby, J. C. Branner and others, to whom reference is made in these pages.

(2) THE AGENCIES ENGAGED IN PROMOTING ROCKWEATHERING.

The expression "rockweathering" as commonly used, is a comprehensive term descriptive of the processes which are so constantly engaged in degrading rock-masses and reducing them to the condition of gravel, sand, and clay, and incidentally to soil. These processes are in part physical and in part chemical in their nature; at times simple, and yet again complex. But, whatever the forces engaged, they are, with a few isolated exceptions, superficial—they work from the surface downwards. However much they may have accomplished since the first rock-masses appeared above the primeval ocean, in no case can the actual amount of débris in situ, have formed at one time more than a scarcely appreciable film over the underlying and unchanged material. The decomposing forces early lose their active principles, and become quite inert at depths comparatively insignificant. It is only where through erosion the results of the disintegration are gradually removed, that the processes have gone on to such an extent as to perhaps quite obliterate thousands of feet of massive rock, and furnished the necessary débris for the great thicknesses of sandstone, slate, and shale, which characterize the more modern horizons. In certain isolated cases, it is true, ascending steam and heated waters arising from unknown depths, have been instrumental in promoting decomposition, as is well illustrated in the areas of decomposed

rhyolites in the Yellowstone National Park. Nevertheless, it is to the exceedingly slow process of superficial weathering that we owe a very large share of the apparent rock decomposition and incidental soil formation.¹

Were it possible it might be well in this discussion to describe each of the involved processes in detail, both in relation to its mode of operation and the results produced. From the fact however, that any one, either physical or chemical, rarely goes on alone, it is thought best to treat the subject as below, and describe in more or less detail the action of (1) the atmosphere, (2) of water in both the solid and liquid form, and (3) that of plant and animal life, finally considering the combined action of all these forces, as manifested on the various types of rock which go to make up the earth's crust.

(a) ACTION OF THE ATMOSPHERE.

Pure dry air under constant conditions of heat or cold, can have, but little effect upon rock-masses either in producing physical or chemical changes. Aided, however, by moisture and temperature variations, it becomes a powerful agent for disintegration as well as for transportation.

In its normal state atmospheric air, as is well known, is a mechanical admixture of four volumes of nitrogen to one of

¹ The reader must keep clearly in mind the distinction between the words *alteration* (Ger. Umwandlung), and *decomposition* (Ger. Verwitterung or Zersetzung) as here used. The one is a more or less deep-seated chemical and molecular process through which a rock may undergo a complete change so far as its mineralogical or lithological nature is concerned while yet retaining its geological identity, as where augite becomes altered to uraltic hornblende, or an eruptive olivine rock (peridotite) becomes altered into serpentine. The second is a wholly superficial change brought about through external agencies and resulting in a more or less complete destruction of the original compounds, loss of material and general breaking down of the mass as a geological body, as when granitic rocks decompose to the condition of quartz sand and kaolin, with the separation of free calcium and alkaline carbonates and oxids of iron and manganese. The line of distinction to be sure cannot in nature be always sharply drawn, and indeed alteration is often but a preliminary to decomposition, though this is by no means universally true, as is shown by the superior resisting power of certain trappean rocks in which the pyroxenic and feldspathic constituents have altered into hard, tough aggregates of free quartz, chlorite and epidote.

oxygen, with minute quantities of carbonic acid (from 2.5 to 3.5 parts in 10,000), and in the vicinity of large cities and in volcanic regions, of appreciable quantities of sulphuric and hydrochloric acids as well. With rare exceptions these last may be considered as existing not as free acids, but in combination as sulphates, and chlorides. This, in addition to their limited distribution justifies us in largely ignoring them in the present discussion.

Nitric acid, nitrogen and ammonia.—Much has from time to time been written regarding the occurrence of nitric acid in the atmosphere, and its supposed significance in relation to the subject under discussion. It seems now, however, to be the generally accepted opinion among chemists, that *free* nitric acid in the atmosphere is a thing of comparative rare occurrence and if occurring at all, is present only in very minute quantities. The researches of Boussingault, Cloez, De Luca and others did, it is true, indicate the presence of the acid, but as ammonia is also almost invariably present in amounts sufficient or even in excess of that needed to combine with it as a nitrate, the conclusion seems unavoidable that in the large majority of cases the presence of free nitric acid is impossible, or it exists only momentarily during times of great electrical disturbance (as during thunder showers). As nitrate of ammonia its presence is almost universal. It is probable that neither these gases nor their salts have any direct influence in promoting rock decomposition. It has been demonstrated, however, that nitrogen compounds and nitrogenous matter in the soil, may become subject to nitrification through the action of bacteria, whereby ammonia, nitrous or nitric acid, carbon dioxide and water are formed, though as Wiley says, "The ammonia and nitrous acid may not *appear* in the soils, as the nitric organism attacks the latter at once and converts it into nitric acid."¹ (See further under Influence of Plant and Animal Life.)

In considering the efficacy of these agents as rock destroyers we must not lose sight of the fact that the supply of nitrogen in the soils is as a rule far too small to supply the demands of

¹ WILEY, Principles and Practice of Agricultural Analysis.

growing plants and it is probable that a very large proportion of that which finds its way there, is quickly taken up again by these organisms, and but little is left to promote decay. It is possible that other salts of ammonium than the nitrate may be locally efficacious. Thus M. Beyer as quoted by Van Den Broeck¹ has shown that the feldspars decompose very rapidly under the influence of water containing ammonium sulphate or even sodium chloride, either of which substance may be found in vegetable soil.

Carbonic acid.—The amount of carbonic acid in the air under natural conditions is not a widely variable quantity excepting near volcanoes and the immediate vicinity of gaseous springs. This has been pretty thoroughly demonstrated by Muntz and Aubin.² In the vicinity of large cities and manufactories consuming great quantities of coal the amount is naturally increased. Although carbonic acid is the most abundant gas given off by decomposing vegetable matter, it has apparently been definitely ascertained that the amount of this gas in the atmospheres of regions of abundant vegetation is no greater than elsewhere. This has been accounted for on the assumption that the gas as fast as liberated is taken up by growing organisms or carried by rains into the soil. Twenty-one tests of the air in various parts of Boston during the spring of 1870, showed the presence of 385 parts of carbonic acid in 1,000,000.

Eleven tests of the winter air in Cambridge yielded 337 parts in 1,000,000.³ Dr. J. H. Kidder found the out-door air of Washington to contain 387 to 448 parts in 1,000,000, while Dr. Agnus Smith after an elaborate series of experiments, reported the atmosphere of Manchester (England) as containing 442 parts in 1,000,000.⁴ These tests are all of atmospheres in the vicinity of cities. Muntz and Aubin, quoted above, found a

¹ Mem. Sur. Les Phenomes D'Alteration Des Depots Superficial, p. 16.

² MUNTZ and AUBIN. Comptes Rendus. 93. 1881, p. 797. Also 96. 1883. pp. 1793-97.

³ Second Annual Report Massachusetts State Board of Health. 1871.

⁴ Air and Rain, p. 52.

general mean of 278 parts in a million for stations in Florida, Mexico, Haiti, Chile and Patagonia, and 296 parts in the north of France. Fischer as quoted by Branner¹ has shown that in rain and snow water the amount of carbonic acid varies between 0.22 per cent. and 0.45 per cent. by volume of water. Assuming that the mean of these figures fairly represent the general average, it is easy, knowing the rainfall of any region to calculate the amount of gas thus annually brought to the surface. Professor Branner has thus calculated that from 3.21 to 11.80 millimeters of carbonic acid gas (CO_2) are annually brought to the surface in certain parts of Brazil. The same method of calculation applied to the various parts of the United States, would give us for the Atlantic coast states 3^{mm}.75; for the upper Mississippi Valley 2^{mm}.5; for the Lower Mississippi Valley 4^{mm}.5, and for the northern Pacific states 6^{mm}.25. As it is mainly when this carbonic acid is thus brought to the surface by rain and snows that its effects become of direct significance in our present work, we may drop the matter here, to be taken up again when considering the chemical action of water.

Oxygen.—Under ordinary conditions oxygen is the most active principle in the atmosphere, and it is to this agent that we owe the process of oxidation whereby silicates and other minerals containing iron in the protoxide state undergo decomposition. Even here, however, oxidation is almost inactive unless aided by moisture and a further discussion of the subject may well be deferred to be taken up again when discussing the action of water.

Heat and cold.—The ordinarily feeble action of the air is greatly augmented through natural temperature variations. That heat expands and cold contracts is a fact too well known to need elaboration here. That however the constant expansion and contraction due to diurnal temperature variations may be productive of weakness and ultimate disintegration in so inert a body as stone, seems not so generally understood, or is at least less well appreciated, and hence a little space is devoted to the

¹ Bull. Geol. Soc. of Am., Vol. VII, 1896, p. 305.

subject here. Rocks, it must be remembered, as the writer has noted elsewhere,¹ are complex mineral aggregates of low conducting power, each individual constituent of which possesses its own ratio of expansion, or contraction, as the case may be. In crystalline rocks these various constituents are practically in contact. In clastic rocks they are, on the other hand, frequently separated from one another by the interposition of a thin layer of calcareous, ferruginous or siliceous matter which serves as a cement. As temperatures rise, each and every constituent expands and crowds with almost resistless force against its neighbor; as temperatures fall, a corresponding contraction takes place. Since in but few regions are surface temperatures constant for any great period of time, it will be readily perceived that almost the world over there must be continuous movement within the superficial portions of the mass of a rock. The actual amount of expansion and contraction of stone under ordinary temperatures, has been a matter of experiment. W. H. Bartlett² has shown that the average rate of expansion for granite amounts to .000004825 inch, per inch of stone, for each degree Fahrenheit; for marble .000005668 inch, and for sandstone .000009532 inch. Adie, in a series of similar experiments found the rate of expansion for granite to be .00000438 inch, and for white marble .00000613 inch.³

Shaler states⁴ that rock surfaces in the eastern United States may be subjected to temperatures varying from 150° F. at midday in summer, to 0° and below in winter. This change of 150° in a sheet of granite 100 feet in diameter would produce a lateral expansion of 0.8685 inch of surface. That this expansion must tend to lessen the cohesion and tear the upper from the deeper lying layers, is self-evident. As exemplifying this, Professor Shaler states that there are on Cape Ann (Massachusetts) hundreds of acres of bare rock surface completely

¹ *Stones for Building and Decoration*, WILEY & SONS, New York.

² *Am. Jour. Science*, Vol. XXII, 1832, p. 136.

³ *Trans. Royal Soc. of Edinburgh*, XIII, p. 366.

⁴ *Proc. Boston Soc. Natural History*, XII, 1869, p. 292.

covered with blocks of stone which have been separated from the mass beneath by just this process.¹

It is natural that this form of disintegration should be most pronounced in massive, close-grained rocks. In regions of great extremes of daily temperature, the rupturing of these masses from the parent ledge is frequently attended by gun-like reports sufficiently loud to be heard at a considerable distance. H. von Streeruwitz states² that the rocks of the Trans Pecos (Texas) region undergo a very rapid disintegration from diurnal temperature variations, which here amount to from 60° to 75° F. He says, "I frequently observed in summer, as well as in winter time, on the heights of the Quitman Mountains, a peculiar crackling noise, and occasionally loud reports . . . and careful research revealed the fact that the crackling was caused by the gradual disintegration and separation of scales from the surface of the rock, and the loud reports of crackling and splitting of huge boulders." The scales thus split off, he says, vary in thickness from one-half to four inches, and their superficial area from a few square inches to many feet. This form of disintegration is necessarily confined to slopes unprotected by vegetation, and is the more pronounced the greater the diurnal vegetation. Dr. Livingston reports that in certain parts of Africa the rock temperatures on the immediate surface rise during the day as high as 137° F., and at night fall so rapidly as to throw off by their contraction sharp angular masses in sizes up to 200 pounds weight. Throughout the desert regions of Lower California, as observed by the writer, the granitic and basic eruptive

¹ The rifting action of heat upon granitic masses is said to have been made a matter of quarry in India. It is stated (*Nature*, January 17, 1895,) that a wood fire built upon the surface of the granite ledge, and pushed slowly forward, causes the stone to rift out in sheets six inches or so in thickness and of almost any desired superficial area. Slabs 60 x 40 feet in area have been thus obtained varying not more than half an inch from a uniform thickness throughout. In one instance mentioned the surface passed over by the line of fires was 460 feet, setting free an area of stone of 740 square feet of an average thickness of five inches. This stone was undoubtedly one of remarkably easy rift, but the case will nevertheless serve our present purposes of illustration.

² Fourth Ann. Rep. Geol. Survey of Texas, 1892, p. 144.

rocks, subjected to very little rainfall, and hence almost completely bare of vegetation, have, under the blistering heat of the desert sun, weathered down into dome shaped masses, their débris in the form of angular bits of gravel being strewn over the plain. Particles of this gravel when compared with those which are a product of chemical agencies are found to differ in that each, however friable, is a complex molecule of quartz, feldspar and mica or whatever may be the mineral composition of the rock from which it derived. Aside from a whitening of the feldspathic constituent, due to the reflection of the light from its parted cleavage planes, scarcely any change has taken place, and indeed it more resembles the finely comminuted material from a rock crusher than a product of natural agencies.

Owing however to the low conducting power of rocks, disintegration from this cause alone can go on to any extent only at the immediate surface, and on flat and level planes where the débris is allowed to accumulate must in time completely cease.¹

It is only on hillsides and slopes or where by the erosive action of running water, or by wind, the débris is gradually removed that such can have any geological significance, although the rate of such disintegration is sufficiently rapid in exposed places to be of serious consequence in stone used for architectural application. (See further under Action of Ice.)

¹ Observations by FORBES (Trans. Royal Society of Edinburgh, Vol. XVI, 1849), showed that at depths of not above twenty-five feet the mean annual temperature was greater than near the surface, these results being confirmatory of those obtained by QUETELET at Brussels. The following tables from FORBES' paper show maximum range of temperatures at varying depths and also the depths at which the annual range is reduced to 0°. 01 centigrade.

I. SHOWING RANGE OF TEMPERATURES FAHR.

Year 1841-1842	Trappean Rock Observatory			Sand Experimental Garden		
	Max.	Min.	Range	Max.	Min.	Range
3 ft	52.85	38.88	13.97	54.50	37.85	17.65
6 "	51.07	40.78	10.29	52.95	39.55	13.40
12 "	49.0	44.2	4.8	50.4	43.5	6.9
24 "	47.5	46.12	1.38	48.1	46.1	2.0

But it is to the action of the air when in motion—to the wind—that is due a very effective part of atmospheric work. Particles of sand drifting along before the wind become themselves agents of abrasion, filing away on every hard object with which they come in contact. As a matter of course this phenomenon is most strikingly active in the arid regions, though the results, when looked for, are by no means wanting in the humid east. It is thought by Professor Egleston that many of the tombstones in the older churchyards of New York City, have become illegible by the wearing action of the dust and sand blown against them from the street. There is among the heterogeneous collections of the National Museum, at Washington, a

Sandstone Craigleigh		
Max.	Min.	Range
53.15	38.25	14.9
51.9	38.95	12.95
50.3	41.6	8.7
48.25	44.35	3.9

II. SHOWING DEPTHS AT WHICH THE ANNUAL RANGE IS REDUCED TO
0°.01 CENT.

Year	Trappean Rock Observatory	Sand Experimental Garden	Sandstone Craigleigh
1837	58.1	72.2	97.3
1838	49.3	61.8	91.0
1839	59.2	63.5	100.0
1840	55.9	67.1	98.8
1841	63.9	68.3	107.4
Mean	57.3	66.6	98.9

Observations on soil temperatures made at the Orono (Maine), Experimental Station, showed the mean daily range of temperatures from April to October, at a depth of 3 inches to be 5°.26; at 6 inches 1°.9; at 9 inches 1°.18; and at 12 inches very slight. At a depth of 1 inch the temperature was lower than that of the air by 2°.4; at 3 inches, by 2°.11; at 6 inches, by 3°.16; at 9 inches, by 3°.94; at 12 inches, by 4°.18; at 24 inches, by 5°.78; and at 36 inches by 7°.10.

The remarkable uniformity of temperatures at comparatively slight depths below the surface is also well illustrated by limestone caverns and in mines. The highest summer temperature of Mammoth Cave being reported as 56° F. and the lowest winter as 52°.5. The mean for the summer being 54° and for the winter 53°.

large sheet of plate glass, once a window in a lighthouse on Cape Cod. During a severe storm of not above forty-eight hours' duration this became on its exposed surface so ground from the impact of grains of sand blown against it, as to be no longer transparent and to necessitate its removal.

Window panes in the dwelling houses of the vicinity are, it is even stated, not infrequently drilled quite through by the same means.

Apply now this agency to a geological field in a dry region. The wind sweeping across a country bare of verdure and parched by drouth, catches up the loose particles of dust and sand and drives them violently into the air in clouds, or sweeps them along more quietly close to the surface where they are at first scarcely noticeable. The impact of a single one of these moving grains on any object with which it may come in contact, is far too small to be appreciable, but the impact of millions acting through days, weeks and years, produces results not merely noticeable but strikingly conspicuous. We have here in fact a natural sand blast, an illustration on a grand scale of a principle in common use in glass cutting and to a small extent in stone cutting also. Constantly filing away on every object with which they come in contact the grains go sweeping on, undermining cliffs, scouring down mountain passes, wearing away the loose boulders and smoothing out all inequalities. Naturally the abrading action on exposed blocks of stone is most rapid near the ground, as here the flying sand grains are thickest. First the sharp angles and corners are worn away, and the masses gradually become pear shaped, standing on their smaller ends. Finally the base becomes too small for support, the stone topples over, and the process begins anew without a moment's intercession and continues until the entire mass disappears—becomes itself converted into loose sand drifted by the wind and an agent for destruction. W. P. Blake was the first, I believe, to call public attention to this phenomenon, having observed it while in the pass of San Bernardino (California) in 1853. G. K. Gilbert has also published some interesting facts as noted by him-

self while geologist of the Wheeler Expedition west of the 100th meridian in 1878. In acting on the hard rocks the sand cuts so slowly as at times to produce only grooved or fantastically carved surfaces often with a very high polish. The geologists of the 40th Parallel Survey in 1878 described like interesting phenomena as observed on the western faces of conglomerate boulders exposed to the sand blasts of the desert regions of Nevada. The surface of the otherwise light colored rock was found to have assumed a dark lead gray hue and a polish equal to that of glass, while the sand had drilled irregular holes and grooves, often three-fourths of an inch deep and not more than an eighth of an inch in diameter, through pebbles and matrix alike.

Even the humid east is not without its illustrations of natural sand-blast carvings. On the shores of Cape Elizabeth, Maine, the cliffs facing toward the open sea are often riddled with peculiarly irregular holes formed by the gyrations of sand grains blown up from the beach below and kept spasmodically in motion by the wind.

(b) CHEMICAL ACTION OF WATER.

Pure water, although an almost universal solvent, nevertheless acts with such slowness upon the ordinary materials of the earth's crust that its results are scarcely appreciable to the ordinary observer. It by no means follows, however, that its effects are not worthy of our consideration here. This is particularly true when we reflect that the results we are discussing are not merely those of days and weeks, but of years even when counted by the tens of thousands and millions. Moreover absolutely pure water, as a constituent of our earth and its atmosphere, presumably does not exist. We have to consider its action as well when contaminated with sundry salts and acids which it almost universally holds, having taken them up in passing through the atmosphere and in filtering through the overlying layer of organic matter and decomposition products which cover so large a portion of the surface of the land. It is when thus contaminated, then, that are manifested the wonder-

ful solvent and other chemical reactions which have been instrumental in promoting rock destruction, and it is here, then, that we will consider the complex chemical processes commonly grouped under the head of oxidation, deoxidation, hydration, and solution.

Oxidation.—Oxidation is perceptibly manifested only in rocks carrying iron either as sulphide, protoxide carbonate, or silicate. The sulphides, in presence of water and when not fully protected from atmospheric influences, readily succumb, producing sulphates, which being soluble are rapidly removed in solution, or hydrated oxides, sulphuretted hydrogen, and perhaps free sulphur. Such an oxidation is attended by an increase in bulk so that if nothing escapes by solution there may be brought to bear a physical agency to aid in disintegration. Weathered rocks containing iron sulphides may not infrequently be found with cubical cavities quite empty or partially filled with the brownish, yellow, or red product of their oxidation, in a more or less powdery condition. Pyrites, though a widespread constituent, is nevertheless a less conspicuous agent in promoting rock decomposition than the protoxide carbonates and silicates. In these the iron passes also over to the hydrated sesquioxide state, as is indicated by the general discoloration whereby the rock becomes first streaked and stained and finally uniformly ochreous. The more common minerals thus attacked are the ferruginous carbonates of lime and magnesia and silicates of the mica, amphibole, and pyroxene groups. As the oxidation progresses the minerals become gradually decomposed and fall away into unrecognizable forms. The red and yellow colors of soils are due invariably to the iron oxides contained by them.

Deoxidation is a less common feature than oxidation. Water carrying quantities of organic acids may, through their influence, take away a portion of the combined oxygen of a sesquioxide, converting it once more into the protoxide state, in which form it may be dissolved and removed as a ferrous carbonate or sulphate. The local bleaching of certain ferruginous

sands and sandstones is due to this action. Through a similar process of deoxidation ferrous sulphates may be converted into sulphides, a process which undoubtedly takes place in marine muds protected by the water from atmospheric action. *Hydration*—the assumption of water—more commonly accompanies oxidation, and indeed is an almost constant accompaniment of rock decomposition, as may be observed in comparing the total percentages of water in fresh and decomposed minerals and rocks, as given in any series of analyses. The amount of water thus taken up is in some cases surprisingly large. This assumption, provided it be not accompanied with an equal loss of other constituents, is attended with an increase in bulk such as may be quite appreciable. In cases where rock disintegration progresses without serious decomposition or surface erosion a corresponding expansion must also take place. The Comte de la Hure, as quoted by Branner,¹ has expressed the opinion that some of the hills of Brazil have actually increased in height through this means. The present writer has calculated that the transition of the granitic rock of the District of Columbia into arable soil must be attended by an increase in bulk amounting to 88 per cent.

Hydration as a factor in rock disintegration is, in the writer's opinion, of more importance than is ordinarily supposed. Granitic rocks in the District of Columbia have been shown² to have become disintegrated for a depth of many feet with loss of but some 13.46 per cent. of their chemical constituents and with apparently but little change in their form of combination. Aside from its state of disintegration the newly-formed soil differs from the massive rock mainly in that its feldspathic and other silicate constituents have undergone a certain amount of hydration. Natural joint blocks of the rock brought up from shafts excavated during the extension of the city waterworks were, on casual inspection, sound and fresh. It was noted, however, that on exposure to the atmosphere such

¹ Bull. Geol. Soc. of America, Vol. VII, 1896, p. 284.

² MERRILL, Bull. Geol. Soc. of America, Vol. VI, p. 341, and Vol. VII, p. 357.

not infrequently shortly fell away to the condition of sand. Closer inspection revealed the fact that the blocks, when brought to the surface, were in a hydrated condition, giving forth a dull instead of clear, ringing sound when struck with a hammer, and showing a lusterless fracture, though otherwise unchanged. That such had not previously fallen away to the condition of sand, it is assumed, was due to the vise-like grasp of the surrounding rock-masses.

Solution.—It is, however, the solvent power of water that most concerns us here, though solution alone plays a comparatively unimportant part upon rocks not first subjected to physical and oxidizing agencies, excepting in the case of those composed essentially of carbonate of lime or magnesia. Rain and nearly all superficial waters as already noted contain traces of carbonic and other organic acids,¹ which act upon the material of the rocks, carrying it away invisibly, but none the less surely.

As long ago as 1848 the Rogers brothers showed² that pure water partially decomposed nearly all the ordinary silicate minerals which form any appreciable part of our rocks. The action of carbonated water upon the minerals in a finely pulverized condition was recognizable in less than ten minutes, but pure water required a much longer time before its effect was sufficient for a qualitative determination. So pronounced was the action

¹ Under this head are included the complex, unstable and little understood products of plant decomposition known as humic, ulmic, crenic and apocrenic acids. These act not merely as reducing agents (from their tendency to themselves undergo oxidation) but are energetic solvents as well, attacking not merely the lime carbonates but also silica and phosphates, arsenates and sulphates of the alkaline earths and the metallic sulphides.

BERTHELOT and ANDRE (*Comptes Rendus Academie de Paris*, 114, 1892, pp. 41-43) have shown that the brown substance of humus and analogous compounds undergo direct oxidation under the influence of the air and sunlight, forming carbonic acid. These reactions are purely chemical, taking place without the intervention of microbes, and are accompanied by a change in color of the original humus. The oxidation is rendered more active through the division and mellowing of the humus by cultivation. Through chemical union of the carbonic acid with certain bases, as lime soda and potash there are formed soluble carbonates which may be leached out by meteoric waters.

² American Journal of Science, Vol. V, 1848.

that the presence of the alkalies of lime and magnesia could be recognized in a single drop of the filtrate from the liquid in which the powdered minerals were digested. By digestion for forty-eight hours in carbonated waters they obtained from hornblende, actinolite, epidote, chlorite, serpentine, feldspar, etc., a quantity of lime, magnesia, oxide of iron, alumina, silica and alkalies amounting to from 0.4 to 1 per cent. of the whole mass. The lime, magnesia and alkalies were obtained in the form of carbonates; the iron, in the case of hornblende, epidote, etc., passing from the state of carbonate to that of peroxide during the evaporation of the solutions. Forty grains of finely pulverized hornblende, digested for 48 hours in carbonated water at a temperature of 60°, with repeated agitation yielded: silica 0.08 per cent.; oxide of iron 0.095 per cent.; lime 0.13 per cent.; and magnesia 0.095 per cent. with traces of manganese. Commenting on these results Bischof remarks¹ that "by repeating this treatment 112 times with fresh carbonated water, a perfect solution might be affected in 224 days." If now he says, "40 grains of hornblende unpowdered, in which, according to the above assumption, the surface is only $\frac{1}{1000000}$ of the powdered, were treated in the same way, and the water renewed every two days, the time required for perfect solution would be somewhat more than six million years." In considering these figures and their practical bearing we must remember that while in nature the quantity of water coming in contact with a crystal imbedded in a rock during a given time is much less than that assumed above, the mineral is undergoing a gradual splitting up, becoming more and more porous, so that the process is gradually accelerated.

Richard Müller has also shown² that carbonic acid waters will act even during so brief a period as seven weeks upon the silicate minerals with such energy as to permit a quantitative determination of the dissolved materials. The accompanying

¹ Chemical and Physical Geology, Vol. I, p. 61.

² Untersuchen über die Einwirkung des kohlensaurehaltigen wasser auf einige Mineralien und Gesteine. Tschermaks Min. Mittheilungen. 1877, p. 25.

table shows (1) the percentages of the various constituents thus taken out by the carbonated water and (2) the total percentages of the materials dissolved. That is to say, the figures 0.1552 given for adular under SiO_2 , indicate that 0.1552 per cent. of the total 65.24 per cent. of the silica contained by the mineral has been removed, and so on. The last column, on the other hand, gives the total per cent. of the entire rock of all the constituents extracted.

Mineral	SiO_2	Al_2O_3	K_2O	Na_2O	MgO	CaO	P_2O_5	FeO	Total
Adular.....	0.1552	0.1368	....	....	.. .	....	....	trace	0.328
Oligoclase...	0.237	9.1713	....	2.367	....	3.213	....	"	0.533
Hornblende .	0.419	trace	....	....	....	8.528	....	4.829	1.536
Magnetite ...	trace	....	....	....	....	....	....	0.942	0.307
Apatite .....	....	....	....	....	....	2.168	1.822	....	2.018
Olivine	0.873	trace	....	....	1.291	trace	....	8.733	2.111
Serpentine ..	0.354	....	....	....	2.649	....	....	1.527	1.211

The summary of his investigation is given as below :

(1) All the minerals tested were acted upon by the carbonated water.

(2) In this process there were formed carbonates of lime, iron, manganese, cobalt, nickel, potash and soda.

(3) In the action of the carbonated waters upon the alkaline silicates like the feldspars, a small amount of silica went always into solution, presumably in the form of hydrate.

(4) Even alumina was dissolved in appreciable quantities.

(5) Adular proved more resisting to the action of the acid than did oligoclase.

(6) The first stage of decomposition in the feldspars was a reddening process; the second, kaolinization.

(7) Hornblende was more easily decomposed than feldspar.

(8) Increase of pressure on the solution was productive of more energetic action than prolonging the time.

(9) Of all the minerals tested, the magnetic iron was least affected.

(10) Apatite was readily acted upon, as could be detected by its appearance under the microscope.

(11) Olivine was the most readily attacked of all the silicates tested, probably twice as easily decomposed as the serpentine.

(12) Magnesian silicates were attacked by the carbonated waters. Hence serpentine cannot be considered a final product of decomposition.¹

Of all the materials forming any essential part of the earth's crust the limestones are most effected by the solvent power of water. It is stated that pure water will dissolve one part in 10,800 when cold and one part in 8.875 when boiling of lime carbonate.

Since rock weathering is, as already stated, a superficial phenomenon, we have to do only with waters of ordinary temperatures and under ordinary conditions of pressure though this expression must not be taken as necessarily meaning *cold* waters, since during the rainy season in tropical countries the waters falling upon the heated rocks may have their temperatures raised as high as 140° F. or even 150° according to A. Caldeleugh.²

It is almost wholly to this solvent action that is due the formation of the multitudinous caverns of limestone regions. Even where caverns are not apparent the corrosive action is evident to the practiced eye. In the quarry regions of Tennessee surface blocks of limestone are often grooved to a depth of an inch or more with wonderful sharpness, simply from the water of rainfalls with its acids absorbed from the atmosphere and surface soils, while in the quarry bed the stone is found no longer in continuous layers, but in disconnected boulder-like masses. In such cases casual examinations give very little clue to the rapidity of the destruction going steadily on, since all is removed in solution excepting the comparatively small amount

¹ Serpentine, however, cannot be properly considered a decomposition product. It is rather a product of *alteration*.

² On the Geology of Rio Janeiro, Trans. Geol. Soc. of London, 2d Ser. Vol. II, 1829.

of insoluble matter (usually clay or silica) existing as an impurity. In these limestone regions the solvent action has not infrequently gone on so extensively as to leave its imprint upon the topographic features of the landscape. The drainage is no longer wholly superficial but by subterranean streams sinking entirely into the ground to reappear again at lower levels, it may be miles away, having traversed the intervening distance in some of the numerous passages (fissures enlarged by solution) with which the rocks abound. Entire landscapes are not infrequently undulating through the abundance of sinkholes—shallow depressions down through which the water has percolated and escaped into the underground passages. An idea of the amount of material thus dissolved may be gained when I state that some 275 tons have been calculated¹ as annually removed from each square mile of Calciferous (Lower Silurian) limestone exposed in the Appalachian region alone, while a well-known English authority² has calculated that with an annual rainfall of 32 inches percolating only to a depth of 18.3 inches, there are annually removed by solution from the superficial portions of England and Wales an average of 143.5 tons per square mile of area. He further calculates that the average amount of carbonate of lime alone annually removed from each square mile of the entire globe amounts to 50 tons. It is to this corrosive action of meteoric waters that still another authority³ would attribute the slight thickness and nodular condition of many beds of Palæozoic limestone. He argues that originally thick bedded limestones have, during the ages subsequent to their formation and uplifting become so impoverished through the dissolving out and carrying away in solution of the lime carbonate, as to have been quite obliterated or reduced to mere nodular bands, and given rise to important palæontological breaks in the geological record. Other than organic acids may locally exert a potent influence.

¹ A. L. EWING, *Am. Jour. of Science*, 1885, p. 29.

² T. MELLARD READE (*Chemical Denudation in Relation to Geological Time*).

³ F. RUTLEY, *the Dwindling and Disappearance of Limestones*, *Quar. Jour. Geol. Soc. of London*, Aug. 1893.

Thus Robert Bell has described the dolomitic limestones underlying the waters along Grand Manitou Island, the Indian peninsula and adjacent portions of Lake Huron and the Georgian Bay, as pitted and honeycombed in a very peculiar and striking manner. This corrosion, it is believed is, produced through the solvent action of sulphuric acid in the water, the acid itself arising from the decomposition of the sulphides of iron pyrites and pyrrhotite, which exist in great quantities in the Huronian rocks to the northward.¹

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¹ Bull. Geol. Soc. of America, Vol. VI, p. 47-304.

(To be continued.)